Separating the Influence of Environment from Stress Relaxation Effects on Dwell Fatigue Crack Growth

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- **Dwell fatigue crack growth (DFCG) resistance influenced by crack tip environmental embrittlement and crack tip stress relaxation behavior.**

- **Both mechanisms are influenced by time and temperature – difficult to separate and quantify the influence of each.**

- **The ability to relax crack tip stresses reduces the crack driving force and thus significantly influences DFCG resistance.**

- **Use of standard linear elastic fracture mechanics stress intensity (LEFM K) driving force for DFCG correlation is questionable due to the visco-plastic issues.**

Approach

- <u>One alloy/grain size</u>: Eliminate effect of composition and grain size variability.

- <u>Environment:</u> Perform cyclic and dwell FCG tests in both air and vacuum.

- <u>Stress Relaxation:</u> Produce wide range of visco-plastic response by significantly varying microstructure through heat treatment and thermal exposures.

- <u>Separate stress relaxation influence from environment</u>: Perform cyclic FCG at various frequencies – identify conditions having similar intrinsic environmental FCG resistance ("iso-resistant").

- Dwell FCG differences among these iso-resistant conditions assumed due to stress relaxation effects.

- Formulate damage tolerance life prediction methodology to account for the differences in DFCG behavior due to variability in visco-plastic response.

Wt. %	Al	B	C	Co	Cr	Mo	Ni	Nb	Ta	Ti	W	Zr
LSHR	3.5	.03	.045	20.4	12.3	2.7	Bal.	1.5	1.5	3.5	4.3	0.05

Seven Heat Treatments Evaluated

Condition	Cooling Rate (°C/min)	Aging Treatment	Thermal Exposure	
FC+2SA	202°C/min	855°C/4 h +775°C/8h	None	Standard
SC+2SA	72°C/min	855°C/4 h +775°C/8h	None	
FC+2SA+440	202°C/min	855°C/4 h +775°C/8h	815°C-440 h	Moderate Thermal Exposure
SC+2SA+440	72°C/min	855°C/4 h +775°C/8h	815°C-440 h	
FC+2SA+2020	202°C/min	855°C/4 h +775°C/8h	815°C-2020 h	Extreme Thermal Exposure
SC+2SA+2020	72°C/min	855°C/4 h +775°C/8h	815°C-2020 h	
FC+NA	202°C/min	None	None	

LSHR

ASTM 8 (15 µm) 100 µm

1 µm | EHT = 6.00 kV | Signal A = InLens | Date :20 Jan 2016
WD = 5.2 mm | Sample ID = U4-L6SC2 | Mag = 25.00 K X
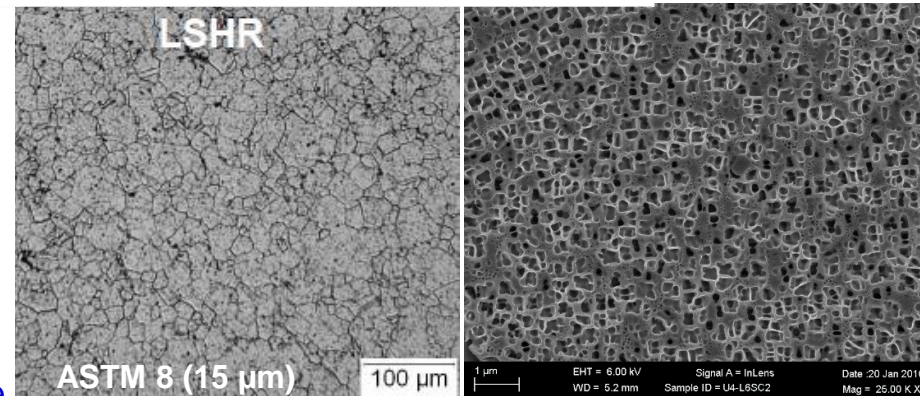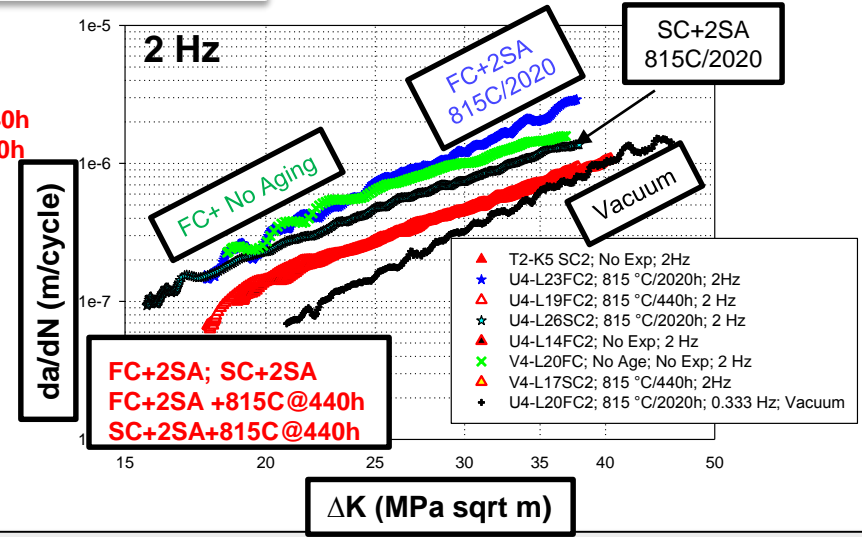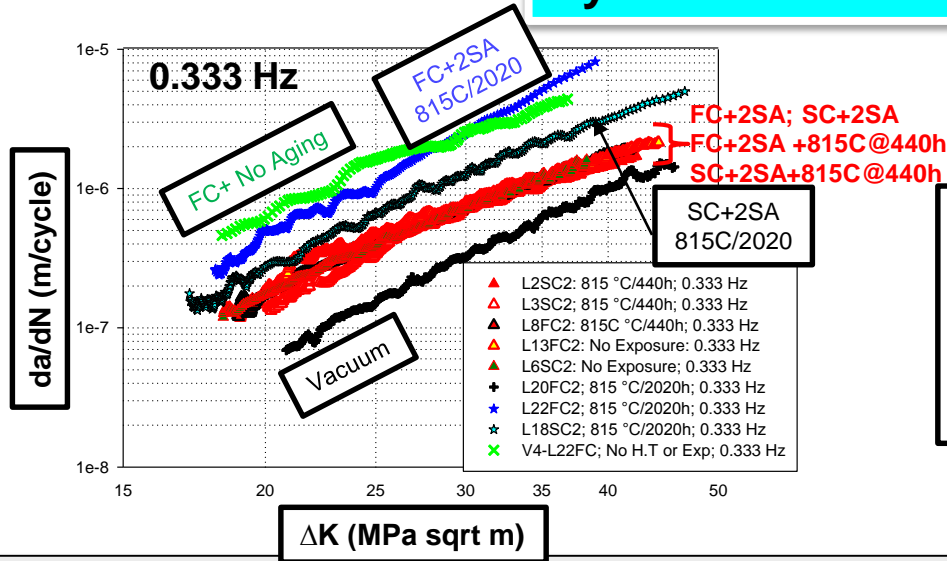
All testing performed at 704 °C

Baseline FCG Testing:
- Cyclic FCG in Air and Vacuum; 0.333 to 30 Hz
- Dwell FCG in Air and Vacuum; 90 sec hold at σ_{max}
- Specimen Geometry: Surface Flaw (K_B bar)
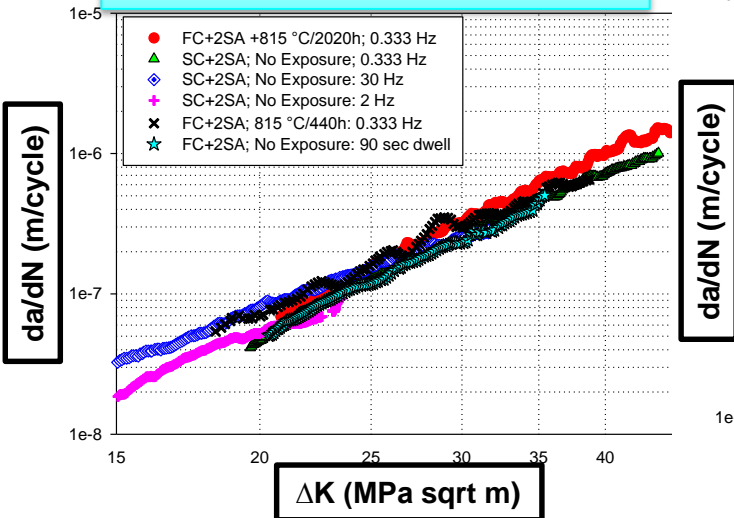
Baseline Stress Relaxation Testing:
- Strained to 1% total strain
- Stress relaxation measured for 100 h.
- Specimen: Cylindrical (4.05 mm diam.)

0.333 Hz

FC+2SA 815C/2020

FC+ No Aging

FC+2SA; SC+2SA
FC+2SA +815C@440h
SC+2SA+815C@440h

SC+2SA 815C/2020

Vacuum

da/dN (m/cycle)

- ▲ L2SC2: 815 °C/440h; 0.333 Hz
- △ L3SC2: 815 °C/440h; 0.333 Hz
- ▲ L8FC2: 815C °C/440h; 0.333 Hz
- △ L13FC2: No Exposure: 0.333 Hz
- ▲ L6SC2: No Exposure; 0.333 Hz
- + L20FC2; 815 °C/2020h; 0.333 Hz
- ✶ L22FC2; 815 °C/2020h; 0.333 Hz
- ✶ L18SC2; 815 °C/2020h; 0.333 Hz
- ✕ V4-L22FC; No H.T or Exp; 0.333 Hz

ΔK (MPa sqrt m)

2 Hz

FC+2SA 815C/2020

SC+2SA 815C/2020

FC+ No Aging

Vacuum

da/dN (m/cycle)

FC+2SA; SC+2SA
FC+2SA +815C@440h
SC+2SA+815C@440h

- ▲ T2-K5 SC2; No Exp; 2Hz
- ✶ U4-L23FC2; 815 °C/2020h; 2Hz
- △ U4-L19FC2; 815 °C/440h; 2 Hz
- ✶ U4-L26SC2; 815 °C/2020h; 2 Hz
- ▲ U4-L14FC2; No Exp; 2 Hz
- ✕ V4-L20FC; No Age; No Exp; 2 Hz
- △ V4-L17SC2; 815 °C/440h; 2Hz
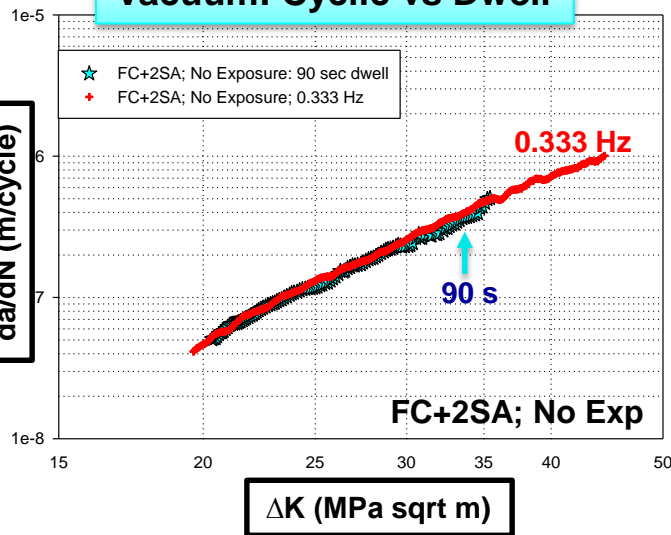- + U4-L20FC2; 815 °C/2020h; 0.333 Hz; Vacuum

ΔK (MPa sqrt m)

- All seven conditions show faster cyclic FCGR in air than in vacuum – environmental effect.
- Same four conditions exhibited similar FCG resistance behavior at both frequencies.
- Assume these conditions posses similar *intrinsic* environmental resistance.
- Any differences in their dwell FCG resistance are then due to stress relaxation effects.
- Microstructures produced by extreme heat treatments/exposures more susceptible to environmental degradation.
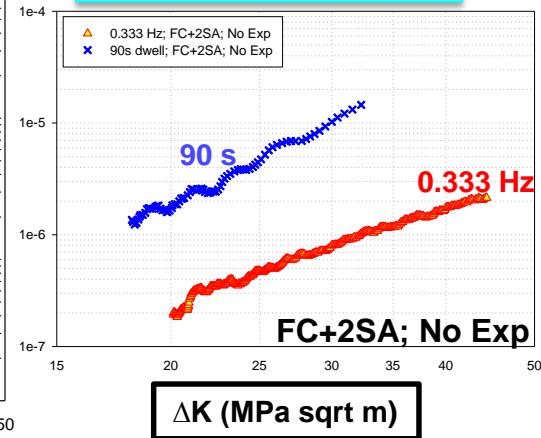
Vacuum: Various Conditions

- FC+2SA +815 °C/2020h; 0.333 Hz
- SC+2SA; No Exposure; 0.333 Hz
- SC+2SA; No Exposure: 30 Hz
- SC+2SA; No Exposure: 2 Hz
- FC+2SA; 815 °C/440h: 0.333 Hz
- FC+2SA; No Exposure: 90 sec dwell

da/dN (m/cycle)

ΔK (MPa sqrt m)

Vacuum: Cyclic vs Dwell

- FC+2SA; No Exposure: 90 sec dwell
- FC+2SA; No Exposure; 0.333 Hz

0.333 Hz

90 s

FC+2SA; No Exp

da/dN (m/cycle)

ΔK (MPa sqrt m)

Air: Cyclic vs Dwell

- 0.333 Hz; FC+2SA; No Exp
- 90s dwell; FC+2SA; No Exp
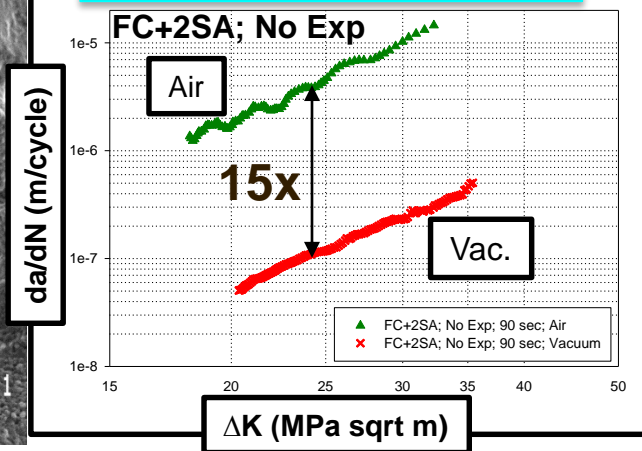
90 s

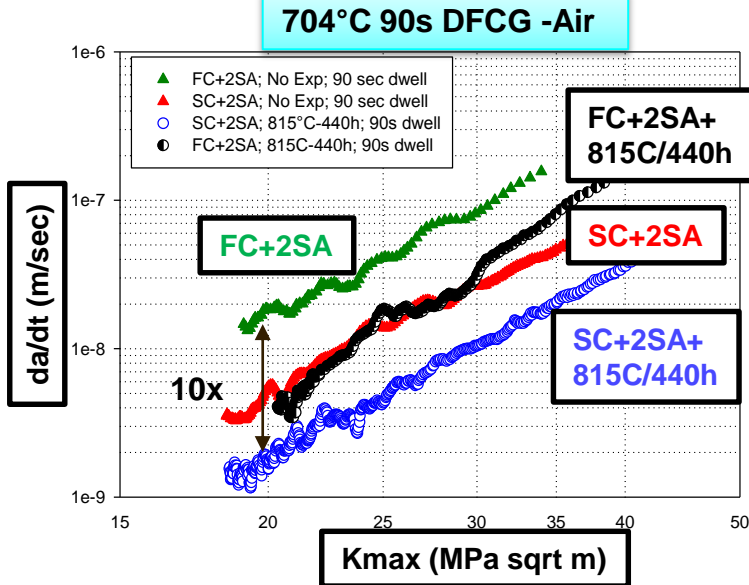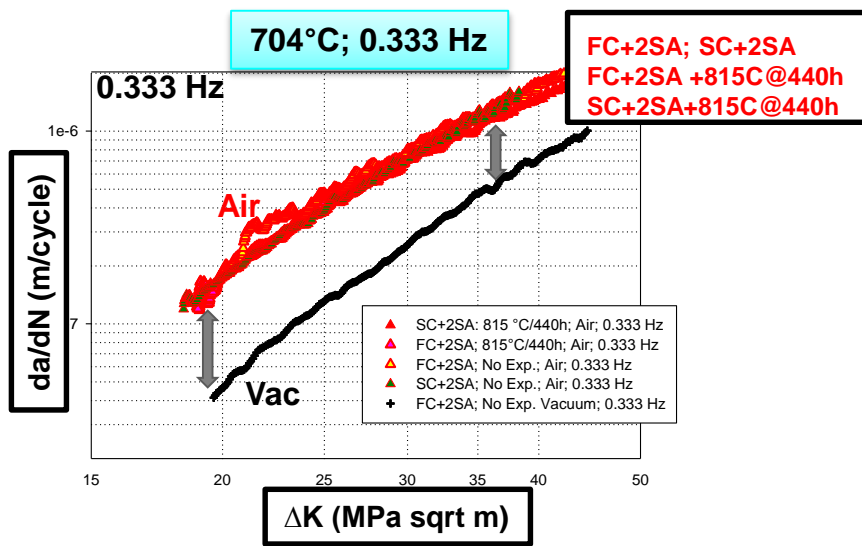**0.333 Hz**

FC+2SA; No Exp

ΔK (MPa sqrt m)

- **Vacuum FCG behavior almost identical irrespective of heat treatment or frequency**

- **90 sec dwell FCG rates in vacuum same as cyclic FCG in vacuum – No Dwell Debit**

- **Creep crack growth does not contribute towards dwell crack growth**
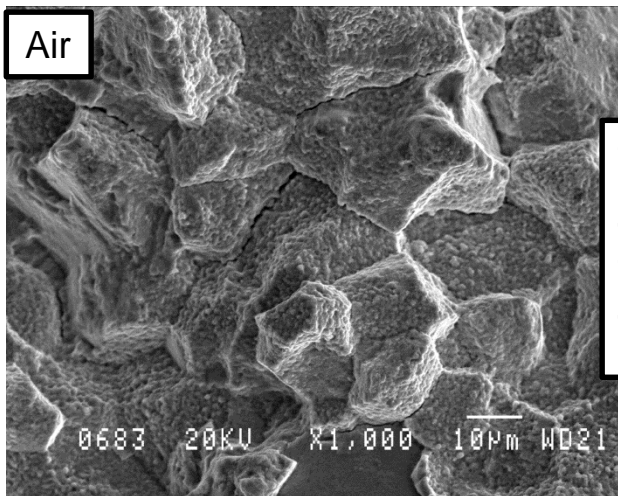
90 s Dwell; Air vs Vacuum
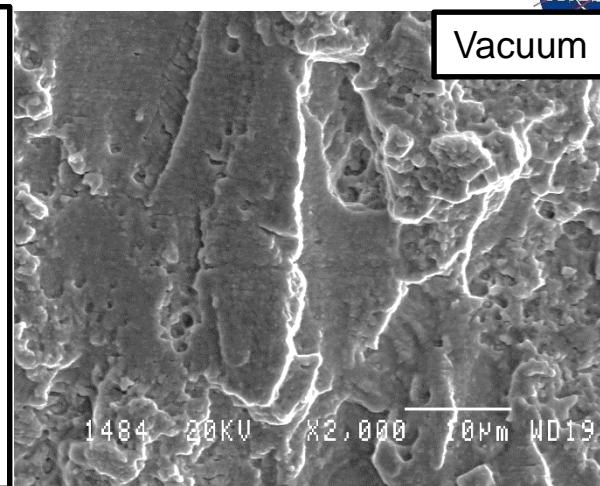
- **Brittle-intergranular failure mode was operative in air for 90 sec dwell.**

- **Only transgranular failure mode operative in vacuum. No evidence of grain boundary sliding or microvoid coalescence found.**

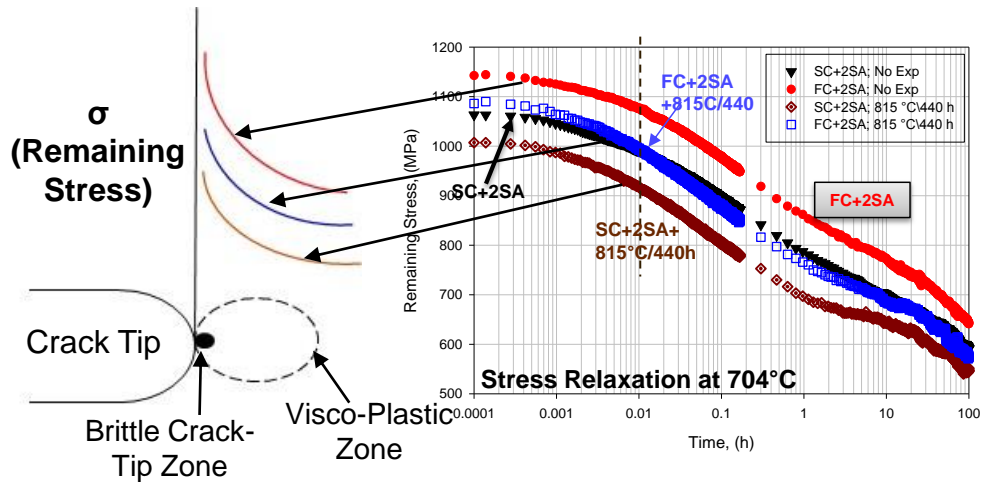- **Classical creep crack growth mechanisms *did not directly* contribute to dwell crack growth.**

704°C; 0.333 Hz

FC+2SA; SC+2SA
FC+2SA +815C@440h
SC+2SA+815C@440h

0.333 Hz

da/dN (m/cycle)

Air

Vac

- SC+2SA: 815 °C/440h; Air; 0.333 Hz
- FC+2SA; 815°C/440h; Air; 0.333 Hz
- FC+2SA; No Exp.; Air; 0.333 Hz
- SC+2SA; No Exp.; Air; 0.333 Hz
- FC+2SA; No Exp. Vacuum; 0.333 Hz

ΔK (MPa sqrt m)

704°C 90s DFCG -Air

▲ FC+2SA; No Exp; 90 sec dwell
▲ SC+2SA; No Exp; 90 sec dwell
○ SC+2SA; 815°C-440h; 90s dwell
◑ FC+2SA; 815C-440h; 90s dwell

FC+2SA+ 815C/440h

da/dt (m/sec)

FC+2SA

SC+2SA

10x

SC+2SA+ 815C/440h

Kmax (MPa sqrt m)

- **Same four iso-resistant conditions – 10x difference in DFCG.**

- **Slower cooling rates and thermal exposures improve DFCG resistance.**

- **Environmental resistance similar – DFCG differences due to stress relaxation.**

- **LEFM Kmax parameter unsuitable for correlating visco-plastic influenced DFCG response.**

Relationship Between Stress Relaxation and DFCG
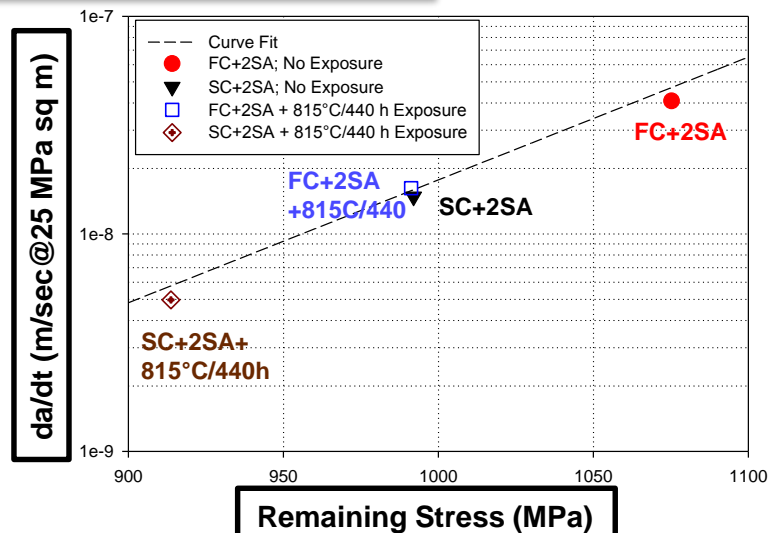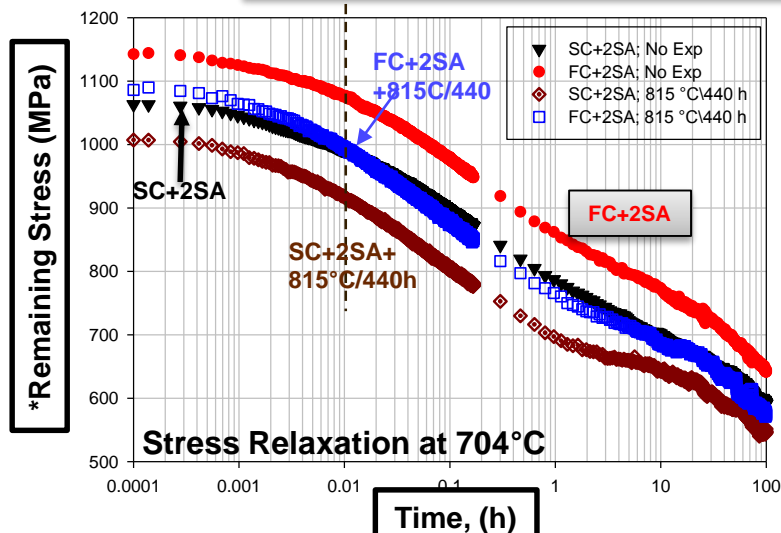
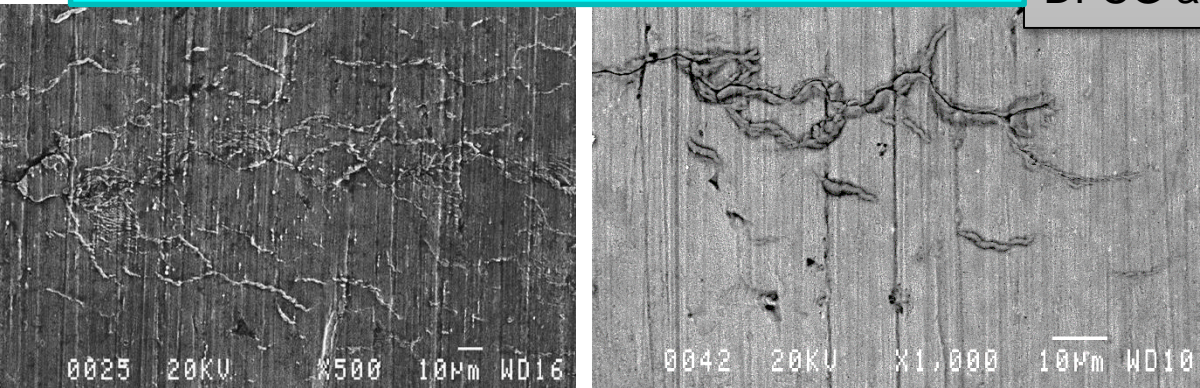

- Stress relaxation stresses decrease with slower cooling rates and ↑thermal exposure.

- Remaining stresses closely correlate with dwell fatigue crack growth
Yet… Classical creep propagation mechanisms DO NOT contribute to crack growth

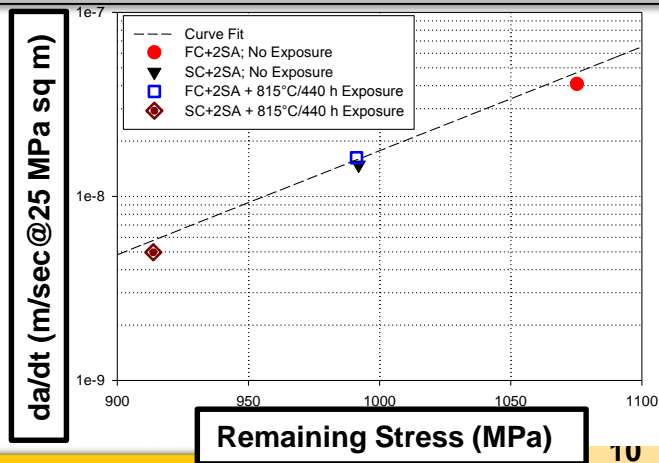- **Why is magnitude of remaining stresses important? <u>What governs the relationship?</u>**

*Remaining Stress = Relaxation Stress

σ (Remaining Stress)

Crack Tip

Brittle Crack-Tip Zone

Visco-Plastic Zone

Stress Relaxation at 704°C

Remaining Stress (MPa)

Time, (h)

SC+2SA; No Exp
FC+2SA; No Exp
SC+2SA; 815 °C\440 h
FC+2SA; 815 °C\440 h

FC+2SA +815C/440
SC+2SA
SC+2SA+ 815°C/440h
FC+2SA

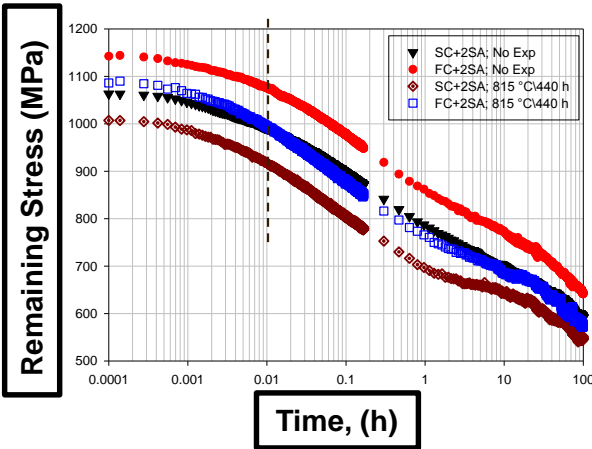Embrittled crack tip region – Interrupted 90s dwell tests

• Dwell cracks grow by a brittle-intergranular process controlled by crack tip tensile stress.

• Magnitude of crack tip tensile stress controls DFCG propagation rates.

• Stress relaxation behavior sets the magnitude of crack tip tensile stresses.

• Strong, yet indirect relationship between DFCG and stress relaxation behavior.

da/dt (m/sec@25 MPa sq m)

Curve Fit
FC+2SA; No Exposure
SC+2SA; No Exposure
FC+2SA + 815°C/440 h Exposure
SC+2SA + 815°C/440 h Exposure

Remaining Stress (MPa)

New Empirical Methodology for Modeling Dwell Crack Growth

Approach: Use stress relaxation results to simulate and normalize the differences in the magnitude of crack tip remaining tensile stresses

Legend:
- SC+2SA; No Exp
- FC+2SA; No Exp
- SC+2SA; 815 °C\440 h
- FC+2SA; 815 °C\440 h

Y-axis: Remaining Stress (MPa)
X-axis: Time, (h)

$$SRF = (\sigma_0/\sigma_m)^4$$

SRF= stress relaxation factor

σ_o= highest remaining stress at the onset of steady state creep (highest remaining stress condition is for FC+2SA condition)

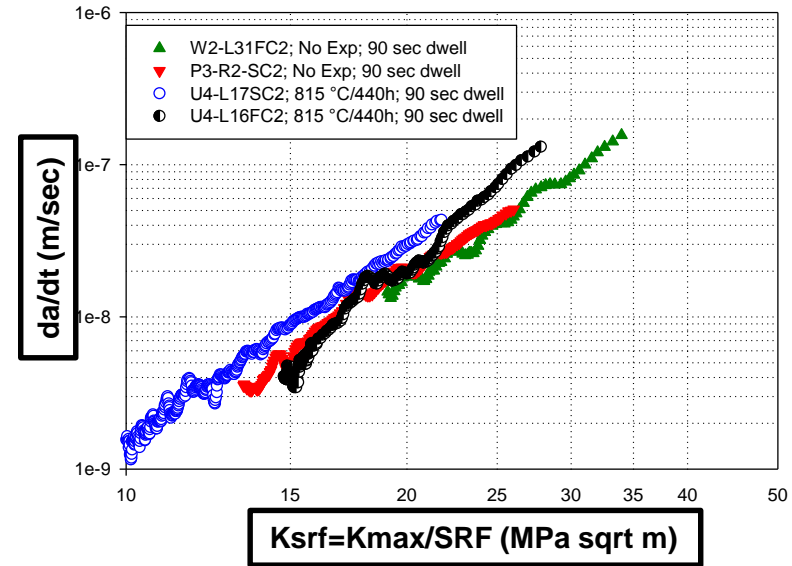**σ_m= remaining stress for other conditions – onset of steady state creep**
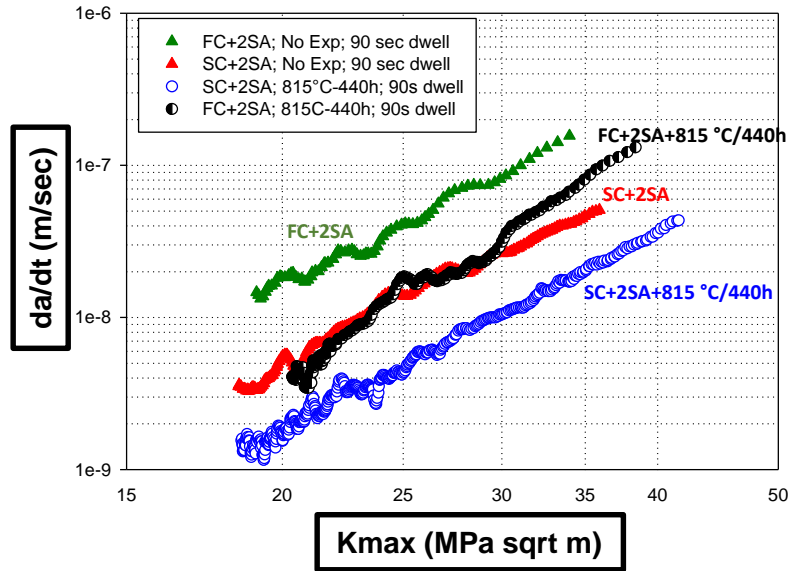
$$\dot{\varepsilon} = A\sigma^{n1}t^m + B\sigma^{n2}$$

*n2= 4 (*steady state creep exponent)

$$Ksrf = Kmax/SRF$$
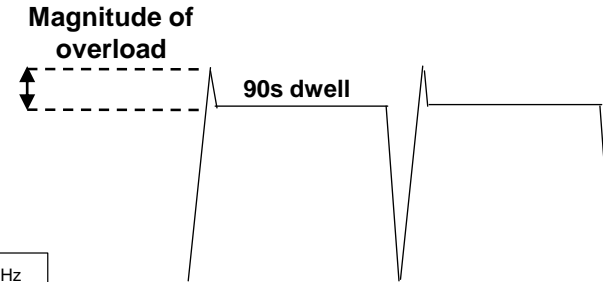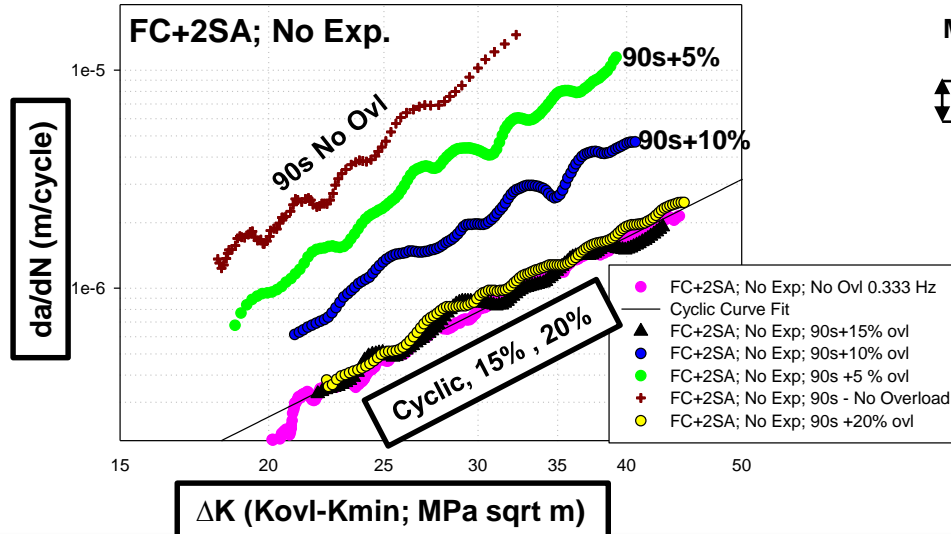
Ksrf – modified stress intensity factor normalized by SRF
Kmax – Applied LEFM stress intensity factor during dwells

Left chart legend:
- ▲ FC+2SA; No Exp; 90 sec dwell
- ▲ SC+2SA; No Exp; 90 sec dwell
- ○ SC+2SA; 815°C-440h; 90s dwell
- ◑ FC+2SA; 815C-440h; 90s dwell

Left chart labels: FC+2SA+815 °C/440h, SC+2SA, FC+2SA, SC+2SA+815 °C/440h
Left chart axes: da/dt (m/sec) vs Kmax (MPa sqrt m)

Right chart legend:
- ▲ W2-L31FC2; No Exp; 90 sec dwell
- ▼ P3-R2-SC2; No Exp; 90 sec dwell
- ○ U4-L17SC2; 815 °C/440h; 90 sec dwell
- ◑ U4-L16FC2; 815 °C/440h; 90 sec dwell

Right chart axes: da/dt (m/sec) vs Ksrf=Kmax/SRF (MPa sqrt m)

• **New parameter able to compensate for a 10x spread in DFCG rates using standard LEFM**

FC+2SA; No Exp.

da/dN (m/cycle)

1e-5

1e-6

90s No Ovl

90s+5%

90s+10%

Cyclic, 15% , 20%

ΔK (Kovl-Kmin; MPa sqrt m)

15   20   25   30   35   40   50

- FC+2SA; No Exp; No Ovl 0.333 Hz
— Cyclic Curve Fit
▲ FC+2SA; No Exp; 90s+15% ovl
● FC+2SA; No Exp; 90s+10% ovl
● FC+2SA; No Exp; 90s +5 % ovl
+ FC+2SA; No Exp; 90s - No Overload
● FC+2SA; No Exp; 90s +20% ovl

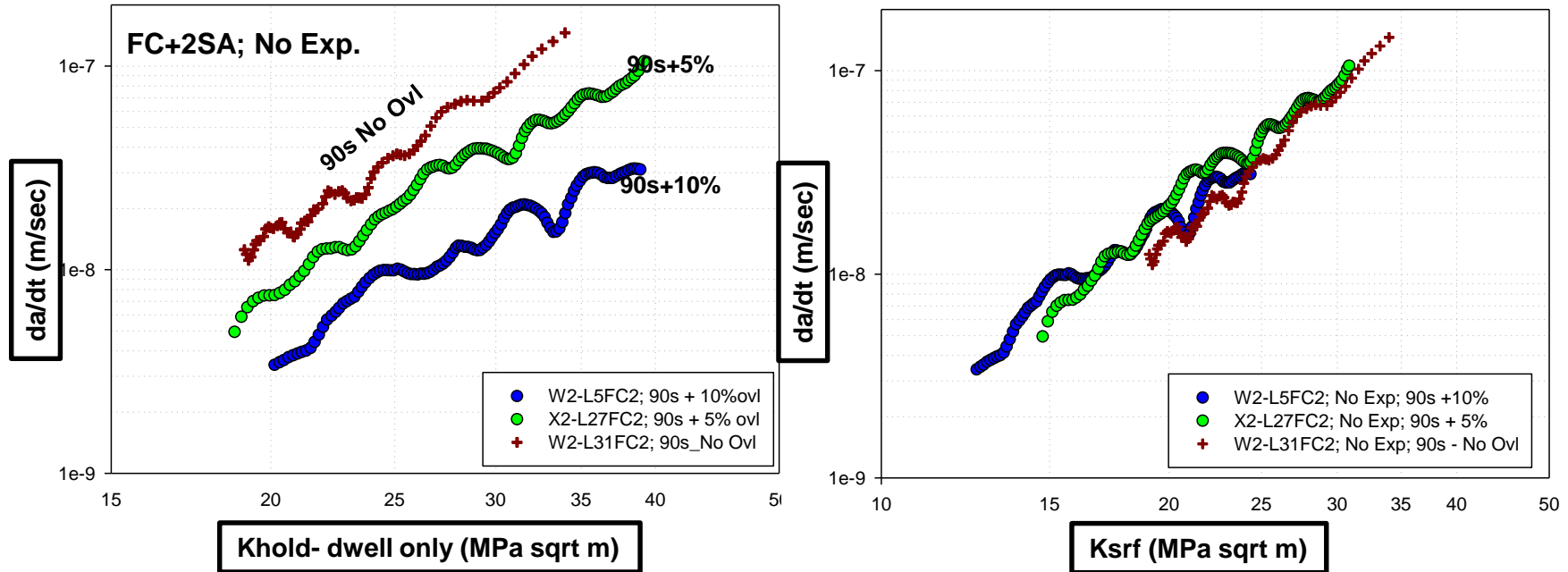Magnitude of overload

90s dwell

- **Small overloads substantially reduce DFCG rates– a significant, unexplained phenomena.**

- **Once dwell effect eliminated, higher overloads _do not_ produce further decrease in DFCG rates.**

FC+2SA; No Exp.

Tensile Loading with Overloads

Stress Relaxation after 1% Strain

0%
5%
10%
15%
20%
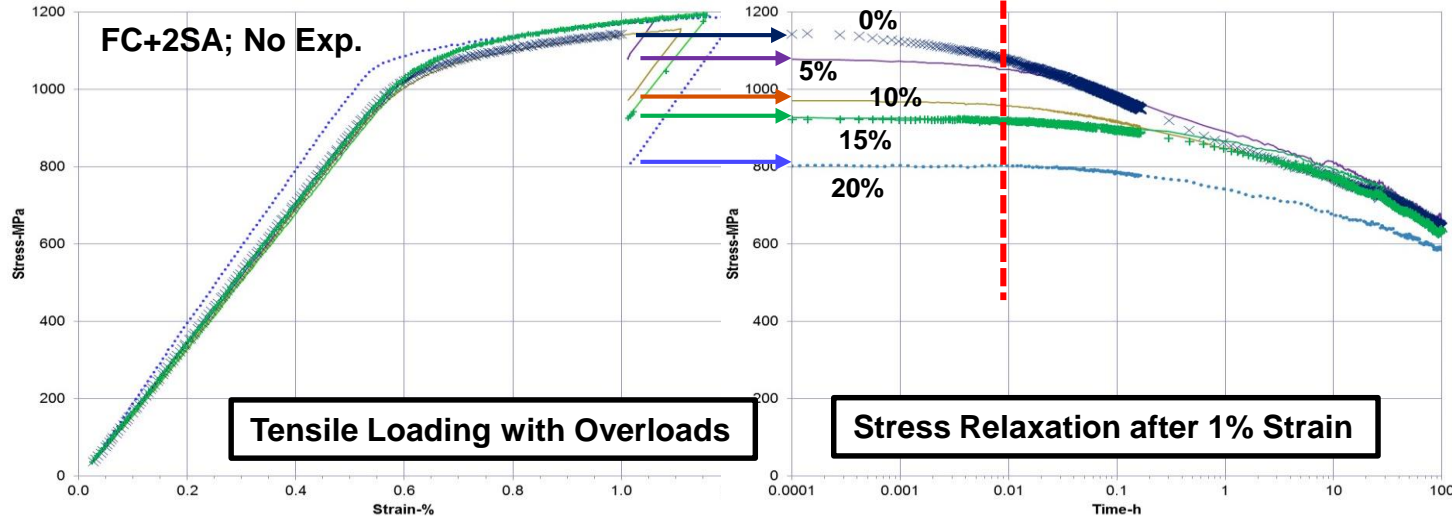
- **Effect of overloads at the crack tip were simulated by tensile-stress relaxation testing.**

- **Small overloads produced significant reduction in remaining stress levels.**

- **Remaining stress after 0.01 h used for Ksrf modeling**

Use of Ksrf to Model Effect of Dwell with Overloads

FC+2SA; No Exp.

90s No Ovl

90s+5%

90s+10%

da/dt (m/sec)

- W2-L5FC2; 90s + 10%ovl
- X2-L27FC2; 90s + 5% ovl
- W2-L31FC2; 90s_No Ovl

Khold- dwell only (MPa sqrt m)

da/dt (m/sec)

- W2-L5FC2; No Exp; 90s +10%
- X2-L27FC2; No Exp; 90s + 5%
- W2-L31FC2; No Exp; 90s - No Ovl

Ksrf (MPa sqrt m)

- **Ksrf formulated to account for dwell effects in DFCG – appropriate only for conditions when dwells contribute to dwell crack growth.**

- **Ksrf/Remaining Stress concept able to correlate dwell FCG with overloads.**

Conclusions

- A new empirical parameter, Ksrf, proposed to correlate DFCG in superalloys.

- The new parameter modifies LEFM_Kmax parameter by accounting for differences in visco-plastic evolution of the magnitude of remaining crack tip axial stresses.

- Magnitude of remaining crack tip axial stresses controls DFCG resistance due to the brittle-intergranular nature of the crack growth process.

- New parameter able to correlate DFCG for conditions with similar intrinsic environmental resistance.

- It is also able to explain the effect of small overloads on DFCG.

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